BABAR-PUB-08/035
SLAC-PUB-13340

Measurement of $B \to X\gamma$ Decays and Determination of $|V_{td}/V_{ts}|$

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(Dated: August 1, 2008)

Using a sample of 383 million $B\overline{B}$ events collected by the *BABAR* experiment, we measure sums of seven exclusive final states $B \to X_{d(s)}\gamma$, where $X_d(X_s)$ is a non-strange (strange) charmless hadronic system in the mass range $0.6 - 1.8\,\mathrm{GeV}/c^2$. After correcting for unmeasured decay modes in this mass range, we obtain a branching fraction for $b \to d\gamma$ of $(7.2 \pm 2.7(stat.) \pm 2.3(syst.)) \times 10^{-6}$. Taking the ratio of X_d to X_s we find $\Gamma(b \to d\gamma)/\Gamma(b \to s\gamma) = 0.033 \pm 0.013(stat.) \pm 0.009(syst.)$, from which we determine $|V_{td}/V_{ts}| = 0.177 \pm 0.043$.

PACS numbers: 13.20.He

The decays $b \to d\gamma$ and $b \to s\gamma$ are flavor-changing neutral current processes forbidden at tree level in the standard model (SM). The leading-order processes are one-loop electroweak penguin diagrams in which the top quark is the dominant virtual particle. In the SM the inclusive rate for $b \to d\gamma$ is suppressed compared to $b \to s\gamma$ by a factor of $|V_{td}/V_{ts}|^2$, where V_{td} and V_{ts} are Cabbibo-Kobayashi-Maskawa matrix elements. Measurements of $|V_{td}/V_{ts}|$ using the exclusive modes $B \to (\rho,\omega)\gamma$ and $B \to K^*\gamma$ [1] have theoretical uncertainties of 7% from weak annihilation and hadronic form factors [2]. A measurement of the inclusive decay $b \to d\gamma$ relative to $b \to s\gamma$ could determine $|V_{td}/V_{ts}|$ with reduced theoretical uncertainties compared to the exclusive modes [3]. In theories beyond the SM [4], new virtual particles may appear differently in the penguin loop diagrams for $b \to d\gamma$ and $b \to s\gamma$ and in the box diagrams responsible for B_d and B_s mixing [5], leading to measurable differences in $|V_{td}/V_{ts}|$ extracted from these two methods.

We present measurements of the rare decays $B \to X_d\gamma$ using seven exclusive final states (see Table I) in the hadronic mass range $0.6 < M(X_d) < 1.0\,\mathrm{GeV}/c^2$ (which contains the ρ and ω resonances), and in the previously unmeasured region $1.0 < M(X_d) < 1.8\,\mathrm{GeV}/c^2$. We combine our results in the two mass regions and make corrections for decay modes that are not reconstructed to obtain an inclusive branching fraction for $b \to d\gamma$ in the mass range 0.6-1.8 GeV/c^2. We perform a parallel analysis of $B \to X_s\gamma$ using the equivalent seven modes (Table I), and determine the ratio of inclusive rates $\Gamma(b \to d\gamma)/\Gamma(b \to s\gamma)$ in the hadronic mass range $0.6 < M(X_d) < 1.8\,\mathrm{GeV}/c^2$.

These measurements use a sample of 383×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector [6] at the PEP-II B factory. The high-energy photon is reconstructed from an isolated energy cluster in the CsI(Tl) calorimeter, which has a shape consistent with a single photon, and an energy $1.15 < E^*_\gamma < 3.5\,\mathrm{GeV}$ in the center-of-mass (CM) frame. We remove photons that can form a π^0 (η) candidate with another photon of energy greater than 30(250) MeV, if the two-photon invariant mass is in the range $105 < m_{\gamma\gamma} < 155\,\mathrm{MeV}/c^2$ ($500 < m_{\gamma\gamma} < 590\,\mathrm{MeV}/c^2$).

TABLE I: The reconstructed decay modes. Charge conjugate states are implied throughout this paper.

$B \to X_d\gamma$	$B \to X_s\gamma$
$B^0 \to \pi^+\pi^-\gamma$	$B^0 \to K^+\pi^-\gamma$
$B^+ \to \pi^+\pi^0\gamma$	$B^+ \to K^+\pi^0\gamma$
$B^+ \to \pi^+\pi^-\pi^+\gamma$	$B^+ \to K^+\pi^-\pi^+\gamma$
$B^0 \to \pi^+\pi^-\pi^0\gamma$	$B^0 \to K^+\pi^-\pi^0\gamma$
$B^0 \to \pi^+\pi^-\pi^+\pi^-\gamma$	$B^0 \to K^+\pi^-\pi^+\pi^-\gamma$
$B^+ \to \pi^+\pi^-\pi^+\pi^0\gamma$	$B^+ \to K^+\pi^-\pi^+\pi^0\gamma$
$B^+ \to \pi^+\eta\gamma$	$B^+ \to K^+\eta\gamma$

Charged pion and kaon candidates are measured in a 1.5 T magnetic field as tracks in a 5-layer silicon vertex detector and a 40-layer drift chamber, with a minimum momentum in the laboratory frame of $300\,\mathrm{MeV}/c$. To differentiate pions from kaons we combine information from the detector of internally reflected Cherenkov light with the energy loss measured in the tracking system. At a typical pion energy of 1 GeV, the pion selection efficiency is 85% and the kaon mis-identification rate is 3%. Kaons are selected by inverting the pion selection criteria. We reconstruct $\pi^0(\eta)$ candidates with momenta greater than $300\,\mathrm{MeV}/c$ from pairs of photons of minimum energy 20 MeV with an invariant mass $107 < m_{\gamma\gamma} < 145\,\mathrm{MeV}/c^2$ ($470 < m_{\gamma\gamma} < 620\,\mathrm{MeV}/c^2$). The selected charged tracks, $\pi^0(\eta)$ candidates, and high-energy photons are combined to form B meson candidates consistent with one of the seven $B \to X_s\gamma$ or $B \to X_d\gamma$ decay modes. For $B \to X_s\gamma$ decays one charged kaon is required, with all other tracks required to be pions. For $B \to X_d\gamma$ decays, all tracks are required to be identified as pions. The charged particles are combined to form a common vertex with a vertex fit probability greater than 2%.

Most of the backgrounds in this analysis arise from continuum $e^+e^- \to q\bar{q}$ events, $q = (u,d,s,c)$, in which a high-energy photon comes from either initial state radiation or the decay of a $\pi^0(\eta)$ meson. We require $R_2 < 0.9$ and $|\cos\theta_T| < 0.8$, where R_2 is the ratio of the second to zeroth Fox-Wolfram moments [7], and θ_T is the angle between the photon and the thrust axis of the rest of the event (ROE) in the CM frame. The ROE includes all the charged tracks and neutral energy in the calorimeter not used to reconstruct the B candidate.

The quantity $\cos\theta_T$ and twelve other variables that distinguish between signal and continuum events are combined in a neural network (NN). These include the ratio R_2', which is R_2 is calculated in the frame recoiling against the photon momentum, the B meson production angle θ^*_B in the CM frame with respect to the beam axis, and five Legendre moments of the ROE with respect to both the thrust axis of the ROE, and the direction of the high-energy photon. Differences in lepton and kaon production between background and B decays are exploited by including five flavor-tagging variables applied to the ROE [8]. We optimize the NN configuration for maximal discrimination between signal and continuum background, which gives 50% signal efficiency and 0.5% misidentification of continuum background.

We use the kinematic variables $\Delta E = E^*_B - E^*_{\mathrm{beam}}$ and

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$m_{\rm ES} = \sqrt{E^{*2}_{\rm beam} - |\vec{p}^{\,*2}_B|}$, where E^*_B and $\vec{p}^{\,*}_B$ are the CM energy and momentum of the B candidate, and $E^*_{\rm beam}$ is the CM energy of one beam. Signal events are expected to have a ΔE distribution centered at zero with a resolution of about 30 MeV, and an $m_{\rm ES}$ distribution centered at the mass of the B meson with a resolution of about 3 MeV/c^2. We consider candidates in the ranges $-0.3\,{\rm GeV} < \Delta E < 0.2\,{\rm GeV}$ and $m_{\rm ES} > 5.22\,{\rm GeV}/c^2$ to incorporate sidebands that allow the combinatorial background yields to be extracted from a fit to the data. On average there are 1.75 candidates per event, and in events with multiple candidates we select the one with the best $\pi^0(\eta)$ mass, or, where there is no $\pi^0(\eta)$ we select the candidate with the best vertex fit probability.

The signal yields in the data are determined from two-dimensional unbinned maximum likelihood fits to the ΔE and $m_{\rm ES}$ distributions of the sums of all seven final states listed in Table I. We consider the following contributions: signal, combinatorial backgrounds from continuum processes, $B \to X\pi^0/\eta$ decays, backgrounds from other B decays, and cross-feed from mis-reconstructed signal $B \to X\gamma$ decays. The fits to the $B \to X_d\gamma$ samples contain a component from misidentified $B \to X_s\gamma$ decays, but we neglect the small $B \to X_d\gamma$ background in the $B \to X_s\gamma$ samples. The B background yields are determined from a Monte Carlo (MC) simulation, whereas the continuum background is allowed to float in the fit.

Each background contribution is modeled by a probability density function (PDF) that is determined from MC. The signal PDFs are the product of one-dimensional $m_{\rm ES}$ and ΔE distributions determined from fits to the $B \to K^*\gamma$ data. For the signal cross-feed component, and the $B \to X_s\gamma$ background in the $B \to X_d\gamma$ fit, we use two-dimensional histogram PDFs to account for correlations. The contributions from $B \to X\pi^0/\eta$ are modeled by Gaussian peaks in both ΔE and $m_{\rm ES}$, where ΔE is displaced by -80 MeV due to the missing photon. The $B \to X_s\gamma$ background in the $B \to X_d\gamma$ sample also peaks with ΔE displaced by -50 MeV due to the kaon misidentification. Continuum and other non-peaking backgrounds are described by an ARGUS shape [9] in $m_{\rm ES}$ and a second-order polynomial in ΔE.

We perform fits separately for $B \to X_d\gamma$ and $B \to X_s\gamma$ and in the two hadronic mass ranges. The signal and continuum yields and the ARGUS and polynomial continuum shape parameters are allowed to vary. We scale the cross-feed contribution proportionally to the fitted signal yield, re-fit, and iterate until the fit converges. The fits for $B \to X_s\gamma$ and $B \to X_d\gamma$ are shown in the low- and high-mass regions in Figs. 1 and 2, respectively.

The signal yields, average efficiencies and partial branching fractions for the sums of the seven decay modes are given in Table II. The reconstruction efficiency depends on the distribution of the signal yield among the final states. For X_s we measure the distribution of the final states in the data, but for X_d there is no statistically useful information, so we model the distribution using the the phase space fragmentation model implemented in JETSET [10].

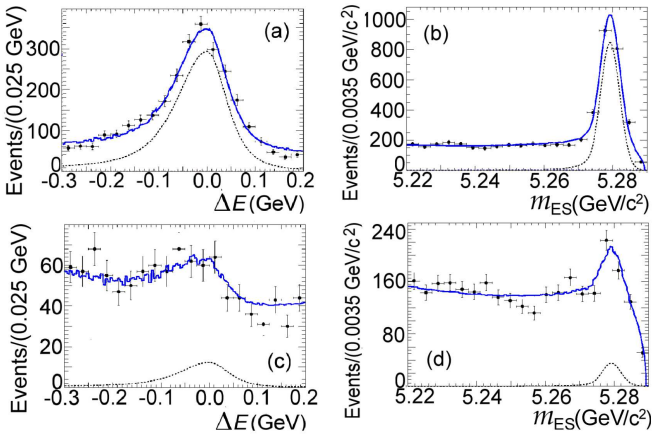

FIG. 1: Projections of the fits to data in the hadronic mass range 0.6-1.0 GeV/c^2. Projection of ΔE with $5.275 < m_{\rm ES} < 5.286\,{\rm GeV}/c^2$ for (a) $B \to X_s\gamma$ and (c) $B \to X_d\gamma$, and $m_{\rm ES}$ with $-0.1 < \Delta E < 0.05$ GeV for (b) $B \to X_s\gamma$ and (d) $B \to X_d\gamma$. Data points are compared with the sum of all the fit contributions (solid line) including the signal (dashed line).

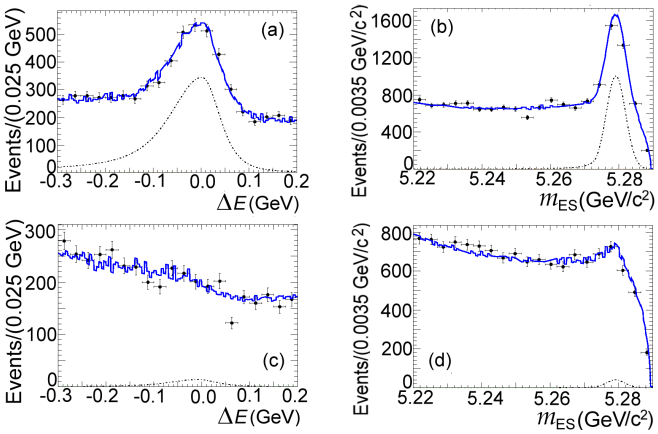

FIG. 2: Projections of the fits to data in the hadronic mass range 1.0-1.8 GeV/c^2. Projection of ΔE with $5.275 < m_{\rm ES} < 5.286\,{\rm GeV}/c^2$ for (a) $B \to X_s\gamma$ and (c) $B \to X_d\gamma$, and $m_{\rm ES}$ with $-0.1 < \Delta E < 0.05$ GeV for (b) $B \to X_s\gamma$ and (d) $B \to X_d\gamma$. Data points are compared with the sum of all the fit contributions (solid line) including the signal (dashed line).

The branching fractions in Table III are obtained after correcting for missing final states. The low mass $B \to X_s\gamma$ measurement is found to be consistent with previous measurements of the rate for $B \to K^*\gamma$ [11], after accounting for the 50% of decays to neutral kaons. For the low mass $B \to X_d\gamma$ region, non-reconstructed ρ and ω decays are small and we find a branching fraction of $(1.2 \pm 0.5) \times 10^{-6}$, consistent with previous measurements of $\mathcal{B}(B \to (\rho,\omega)\gamma)$ [1]. In the high mass region, we correct for missing final states with ≥ 5 stable particles, or with multiple π^0s, using the fragmentation model

TABLE II: Signal yields (N_S), average efficiencies (ϵ) and partial branching fractions ($\mathcal{B}$) for the measured decay modes. The first error is statistical, the second systematic.

$M(X)[\,\mathrm{GeV}/c^2]$	N_S	ϵ	$\mathcal{B}(\times 10^{-6})$
$0.6 < M(X_s) < 1.0$	1543 ± 46	8.5%	$23.7 \pm 0.7 \pm 1.7$
$0.6 < M(X_d) < 1.0$	66 ± 26	7.0%	$1.2 \pm 0.5 \pm 0.1$
$1.0 < M(X_s) < 1.8$	2279 ± 75	6.1%	$48.7 \pm 1.6 \pm 4.1$
$1.0 < M(X_d) < 1.8$	107 ± 47	5.2%	$2.7 \pm 1.2 \pm 0.4$

TABLE III: Branching fractions $\mathcal{B}(\times 10^{-6})$ in the two hadronic mass regions $M(X)[\,\mathrm{GeV}/c^2]$, after correcting for missing final states, and the ratios of $\mathcal{B}(b \to d\gamma)$ to $\mathcal{B}(b \to s\gamma)$. The first errors are statistical, and the second are systematic, including the fragmentation of the hadronic system.

$M(X)$	$\mathcal{B}(b \to d\gamma)$	$\mathcal{B}(b \to s\gamma)$	$\mathcal{B}(b \to d\gamma)/\mathcal{B}(b \to s\gamma)$
$0.6 - 1.0$	$1.2 \pm 0.5 \pm 0.1$	$47 \pm 1 \pm 3$	$0.026 \pm 0.011 \pm 0.002$
$1.0 - 1.8$	$6.0 \pm 2.6 \pm 2.3$	$168 \pm 14 \pm 33$	$0.036 \pm 0.015 \pm 0.009$
$0.6 - 1.8$	$7.2 \pm 2.7 \pm 2.3$	$215 \pm 14 \pm 33$	$0.033 \pm 0.013 \pm 0.009$

described above.

The sources of systematic uncertainties in the measurement of the branching fractions are listed in Table IV. These include uncertainties on track reconstruction efficiency, γ and π^0/η reconstruction, the π^0/η veto, the NN selection, and the number of $B\overline{B}$ pairs. The 2% uncertainty on correct kaon/pion particle identification, and the 20% uncertainty on kaon misidentification, which is a systematic on the fixed $b \to s\gamma$ background in the $B \to X_d\gamma$ fits, do not cancel in the ratio. The systematic errors associated with the variation of the fit PDFs also do not cancel because of the very different signal to background ratios in the two samples. We vary the signal PDF parameters within the range allowed by the fit to the $B \to K^*\gamma$ data. The normalization of the signal cross-feed is varied by $\pm 30\%$, and the contribution of $B \to X\pi^0/\eta$ by $\pm 100\%$, in accordance with MC studies. The remaining peaking B backgrounds, including the $B \to X_s\gamma$ contribution in the $B \to X_d\gamma$ sample, are varied by $\pm 20\%$. We use simulated signal and background event samples to assign a systematic uncertainty due to the potential for bias in the fit method.

TABLE IV: Systematic errors on the measured partial and total branching fractions $\mathcal{B}$. The final column shows systematic errors that do not cancel in the ratio of rates $\Gamma(b \to d\gamma)/\Gamma(b \to s\gamma)$.

Systematic	$M(X_s)$		$M(X_d)$		X_d/X_s
Error Source	0.6-1.0	1.0-1.8	0.6-1.0	1.0-1.8	Ratio
Tracking	1.7%	1.7%	1.7%	1.7%	
High-energy photon	2.5%	2.5%	2.5%	2.5%	
π^0/η reconstruction	1.7%	1.7%	1.7%	1.7%	
π^0/η veto	1.0%	1.0%	1.0%	1.0%	
K/π identification	2.0%	2.0%	2.0%	2.0%	2.0%
Neural network	5.0%	5.0%	5.0%	5.0%	
$B\overline{B}$ pair counting	1.1%	1.1%	1.1%	1.1%	
Fit PDFs	2.4%	3.6%	7.0%	8.3%	8.7%
Backgrounds	0.3%	0.4%	2.4%	6.1%	5.4%
Fit bias	0.4%	1.7%	0.4%	3.3%	3.0%
Fragmentation		3.6%		7.7%	8.5%
Partial $\mathcal{B}$	7.0%	11.4%	10.0%	14.8%	13.8%
Missing ≥ 5 body		5.6%		25.8%	21.0%
Other missing states		17.0%		23.8%	7.1%
Spectrum Model		1.8%		1.6%	
Total $\mathcal{B}$	7.0%	21.2%	10.0%	38.1%	26.1%

There is an additional systematic error on the efficiency due to the uncertainties in the measured fragmentation of the X_s hadronic system into the seven $B \to X_s\gamma$ final states. The equivalent error for $B \to X_d\gamma$ is obtained from the difference between our fragmentation model applied to $B \to X_d\gamma$ and the fragmentation observed in $B \to X_s\gamma$ data. We assume that these errors are independent and so do not cancel in the ratio of branching fractions.

Table IV also shows the systematic errors associated with correcting the partial branching fractions for the missing final states. There is no information from the data on the missing fraction of high multiplicity final states with ≥ 5 stable hadrons, or on the missing fraction of other final states with ≥ 1 π^0 or η mesons. We vary these fractions by $\pm 50\%$ of their values from the default phase space fragmentation. We motivate our choice of a $\pm 50\%$ variation using signal models, for which we mix a combination of resonances as 50% fractions of $B \to X_s\gamma$ and $B \to X_d\gamma$ in the mass range $1.0 - 1.8\,\mathrm{GeV}/c^2$. These give missing fractions close to the lower limits from the $\pm 50\%$ variations. The missing fraction errors partially cancel in the ratio when the $\pm 50\%$ variations are made in the same direction for $b \to d\gamma$ and $b \to s\gamma$.

We take the spectral shape of the high-energy photon from [12] with the kinetic parameters $(m_b, \mu_\pi^2) = (4.65\,\mathrm{GeV}/c^2, -0.52\,\mathrm{GeV}^2)$ extracted from fits to $b \to s\gamma$ and $b \to c\ell\nu$ data [13]. We vary these shape parameters in a correlated way between $(m_b, \mu_\pi^2) = (4.60\,\mathrm{GeV}/c^2, -0.60\,\mathrm{GeV}^2)$ and $(m_b, \mu_\pi^2) = (4.70\,\mathrm{GeV}/c^2, -0.45\,\mathrm{GeV}^2)$. There are systematic errors on the branching fractions from these variations, but they are small and cancel in the ratio. The fraction of the spectrum in the mass range 0.6-1.8 GeV/c^2 is $(51 \pm 4)\%$ for $b \to d\gamma$ and $(50 \pm 4)\%$ for $b \to s\gamma$. We do not extrapolate the ratio of branching fractions to $M_X > 1.8\,\mathrm{GeV}/c^2$, so these errors, which mostly cancel in the ratio, are not included in Table IV. If we make this correction, we obtain $\mathcal{B}(b \to d\gamma) = (1.4 \pm 0.5 \pm 0.4 \pm 0.1) \times 10^{-5}$ and $\mathcal{B}(b \to s\gamma) = (4.3 \pm 0.3 \pm 0.7 \pm 0.2) \times 10^{-4}$, where the first error is statistical, the second systematic and the third accounts for the uncertainty in extrapolating to the full mass range. The result for $B \to X_s\gamma$ is consistent with the measured inclusive $b \to s\gamma$ branching fraction of $(3.55 \pm 0.24) \times 10^{-4}$ [11].

We convert the ratio of branching fractions from the full mass range 0.6-1.8 GeV/c^2, $\Gamma(b \to d\gamma)/\Gamma(b \to s\gamma) =$

$0.033 \pm 0.013 \pm 0.009$, into a value for $|V_{td}/V_{ts}|$ using Table 1 and Equation (26) of [3]. The result is $|V_{td}/V_{ts}| = 0.177 \pm 0.043 \pm 0.001$, where the first error is experimental, including systematic errors, and the second error is theoretical. The theoretical error includes uncertainties on the CKM parameters $\bar{\rho}$ and $\bar{\eta}$, and on $1/m_c^2$ and $1/m_b^2$ corrections, but does not include an uncertainty for the restriction of the measurement of the ratio to hadronic masses below $1.8\,\mathrm{GeV}/c^2$.

As a check, we use the low mass region to determine $|V_{td}/V_{ts}|$ using predictions for exclusive $B \to (\rho,\omega)\gamma$ and $B \to K^*\gamma$ from [2]. We find $|V_{td}/V_{ts}| = 0.214 \pm 0.046 \pm 0.028$ where the first error is experimental and the second is theoretical. This is in good agreement with previously published results [1].

In summary we have made the first measurement of $B \to X_d\gamma$ decays in the hadronic mass range up to $1.8\,\mathrm{GeV}/c^2$, and have extracted $|V_{td}/V_{ts}|$ from an inclusive model with small theoretical uncertainties. These results are consistent with the measurements of $|V_{td}/V_{ts}|$ from the exclusive decays $B \to (\rho,\omega)\gamma$ [1], and with B_s/B_d oscillations [5].

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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